THE RELATION BETWEEN HEIGHT PATTERNS AT 500 MB. AND 100 MB.

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[Manuscript received June 5, 1959; revised July 24, 1959]

ABSTRACT

The flow at 500 mb. is compared with that at 100 mb. With the exception of the polar vortex, the patterns at the two levels tend to show a distinct similarity, with the major exception that small-scale features at 500 mb. are not present at 100 mb.

In middle latitudes, the wind speeds at the two levels are of the same order of magnitude, with a systematic excess of the 100-mb. speeds over the 500-mb. speeds at latitudes 30° and farther south.

In the region of the polar vortex, heights at the two levels are still well correlated. Variations in height over long periods tend to be much larger at 100 mb. than at 500 mb. Similarly, the winds at 100 mb. are much stronger than those at 500 mb.

1. INTRODUCTION

In middle latitudes, the intensity of the winds generally increases through the troposphere and decreases above. It might be expected, therefore, that there would correspond to a given level in the troposphere, a level in the stratosphere at which the wind speeds are the same. This hypothesis is based, in part, on the well-known fact that, in middle latitudes, the change from a warm to a cold upper troposphere at a given station is compensated by a change from a cold to a warm lower stratosphere and vice versa.

Since the 500-mb. level has become the standard level for research and forecasting in the middle troposphere, a "matching" level to 500 mb. in the stratosphere might prove convenient. Fortunately, in middle latitudes, such a "matching" level is often not far from 100 mb., which itself is a mandatory surface.

Of course, the flow at 500 mb. and 100 mb. may be different for several reasons. In the first place, the troughs and ridges with shorter wavelengths at 500 mb. are damped upward and do not appear at 100 mb. This is brought out by the difference in the spectra of height or winds at two levels, which show in every case that the 500-mb. flow contains more high frequency variations compared to low frequency variations than does the 100-mb. flow. Because of this difference between the levels, similarity between the flows at the two levels is enhanced if the flow at 500 mb. is smoothed in some manner. Some experimentation has indicated that the 20° diamond space-mean at 500 mb. (Berry, Haggard, and Wolff [1]) is most satisfactory for this purpose.

Similarly, if the 500-mb. heights or winds are averaged over a time interval equal to or greater than the period of the systems to be averaged out, the two levels can be compared conveniently. In practice, 4-day averages have been employed at both levels in some of the studies presented in this paper; such averages tend to eliminate small-scale flow at 500 mb. and errors at 100 mb.; further, such averages can be estimated at 100 mb. even if a portion of the observations is missing.

Exact equality between smoothed 500-mb. charts and 100-mb. charts can be expected only if tropospheric warming and stratospheric cooling between these two levels exactly compensate. There are several reasons why such compensation may not occur: in the Tropics, the tropopause may be near 100 mb., so that the temperature changes between 500 mb. and 100 mb. are almost entirely tropospheric. In those cases, the wind, on the average, increases from the 500-mb. level up to near 100 mb., so that the winds at 100 mb. exceed the winds at 500 mb.

In contrast, at high latitudes, the tropopause tends to be quite low, so that, if there is stratospheric and tropospheric compensation, the winds at 100 mb. are slower than those at 500 mb. However, it will be seen later that compensation between stratospheric and tropospheric temperatures does not always occur. If the region in question is influenced by the "polar regime" (to be defined later), temperature changes tend to be of the same sign at all levels, and wind changes, as well as the winds themselves, are much greater at 100 mb. than at 500 mb. Hence, the comparison between smoothed 500-mb. flow and 100-mb. flow will indicate what regime is dominant over a given region.
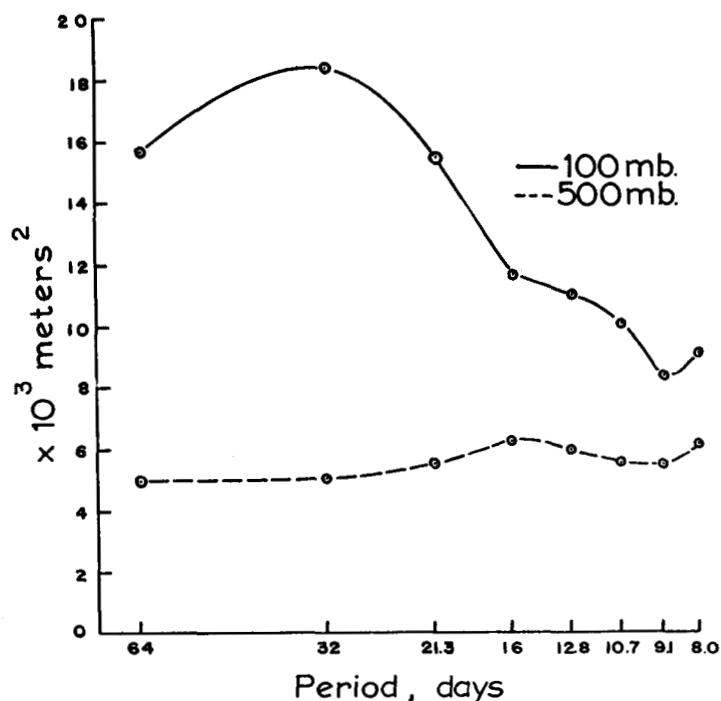
FIGURE 1.—The 100-mb. and 500-mb. height spectra within the polar regime. Data are averages from selected Canadian stations: Frobisher, Arctic Bay, Coral Harbour and Baker Lake for winter 1953–54; and Alert, Port Harrison, Resolute, and Baker Lake for winter 1956–57.
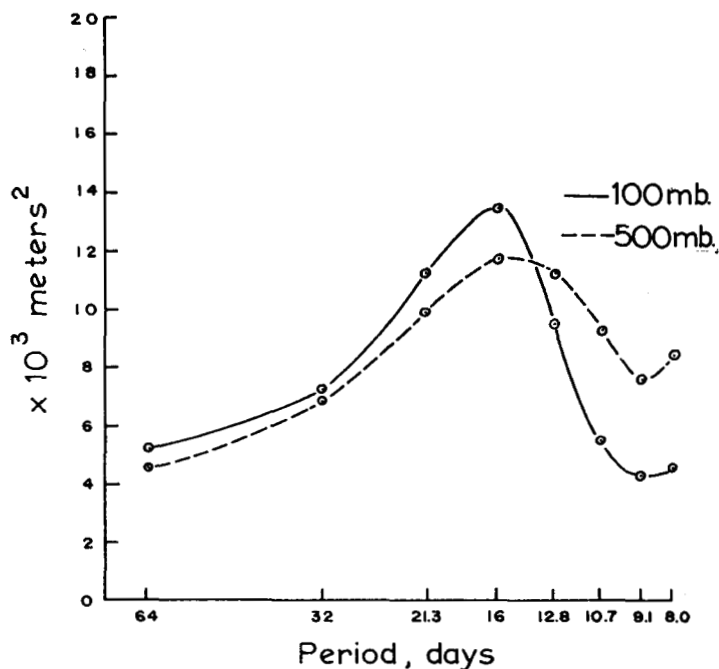

FIGURE 2.—The average 100-mb. and 500-mb. height spectra outside the polar regime, for winters 1955–56 and 1956–57 for Chaumont, France and Nome and Annette Island, Alaska.

2. CLASSIFICATION OF REGIMES AT 100 MB.

Throughout much of the lower stratosphere, contour heights decrease toward the pole and temperatures increase toward the pole. This behavior is not found in the upper stratosphere, above the 50-mb. level. For this reason, the regime in which the temperature increases poleward will be referred to as LSR (lower-stratosphere regime). The LSR extends from about 30° latitude to the poles in summer, and to about 55°, on the average, in winter. Since contour height gradients and temperature gradients oppose each other, the wind speed decreases upward in the LSR. Further, the LSR is characterized by warm troughs and cold ridges, which also decrease upward in intensity. In other words, patterns in the LSR increase in intensity downward, and are, presumably, most strongly developed near the tropopause; therefore, they are closely related to tropospheric patterns.

Within the 55° latitude circle in winter on the average, temperatures and heights both decrease poleward; westerly winds increase upward in intensity. This regime, called the PR (polar regime), is characterized by warm Highs and cold Lows. Its main feature is usually a cold Low, increasing upward in intensity, which will be called the "polar vortex." From studies of the radiation budget of the stratosphere by Ohring [8], the existence of this

vortex can be said to be a result of strong radiational cooling of the stratosphere in the region of the polar night. The reader is referred to Kochanski [7], Godson and Lee [4], and Godson et al. [3] for further details.

Between the PR and the LSR is located the PRB (for polar-regime boundary). This is a band of relatively high temperatures. It is, however, not necessarily the warmest region at 100 mb. Frequently, warm regions associated with cold tropospheric Lows occur in these latitudes. The heights are relatively low so that we deal with warm Lows characteristic of the LSR. Rather, the PRB must be defined as a rather narrow circumpolar region which separates systems intensifying upward from systems decreasing upward. Further, it separates regions in which local temperature and height changes have the same sign (PR) from regions where they have opposite sign (LSR). Finally, winds increase upward in the PR and decrease upward in the LSR. Theoretically, any one of these criteria can be used to locate the PRB. In practice, the easiest method seems to be a careful isotherm analysis indicating the transitions from cold to warm ridges and warm to cold troughs.

Neither the LSR, PR, nor PRB remain symmetrical with respect to the pole. The center of the polar vortex at 100 mb. has been observed to move 20° away from the pole and the PRB to extend down to latitude 40°. The polar vortex center tends to drift very slowly, may take quite different positions in different winters, and appears to
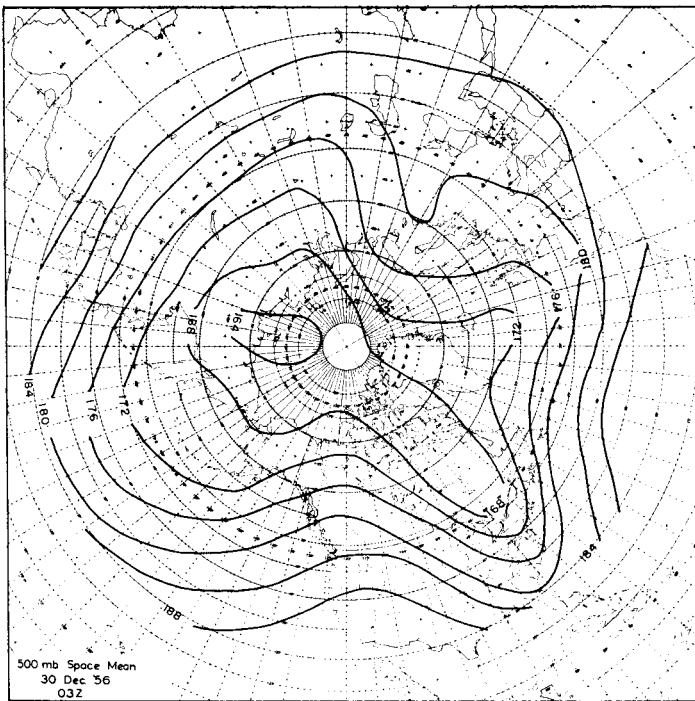
FIGURE 3.—20° diamond space-mean for 500 mb., 0300 GMT, December 30, 1956. Contours labeled in hundreds of feet.
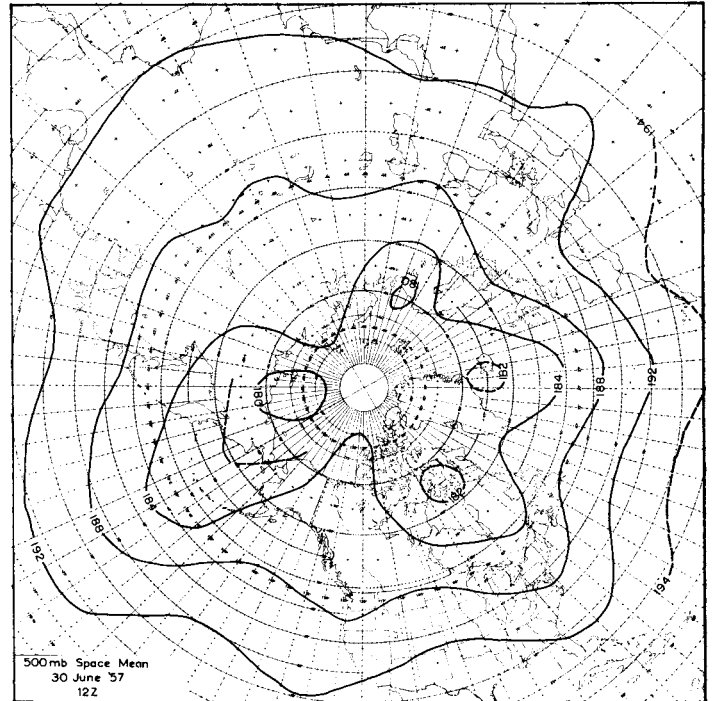

FIGURE 5.—20° diamond space-mean for 500 mb., 1200 GMT, June 30, 1957. Contours labeled in hundreds of feet.
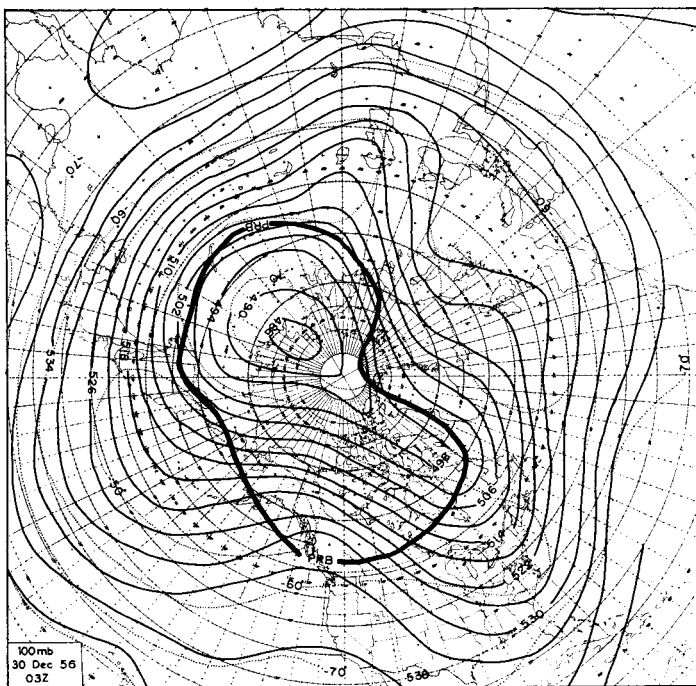

FIGURE 4.—100-mb. chart, 0300 GMT, December 30, 1956. Contours labeled in hundreds of feet. Polar regime boundary is indicated.
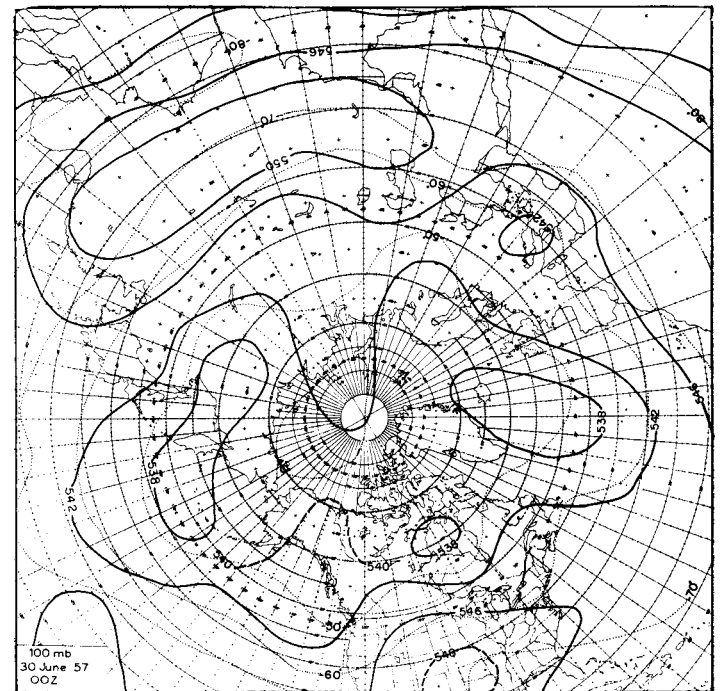

FIGURE 6.—100-mb. chart, 0000 GMT, June 30, 1957. Contours labeled in hundreds of feet.
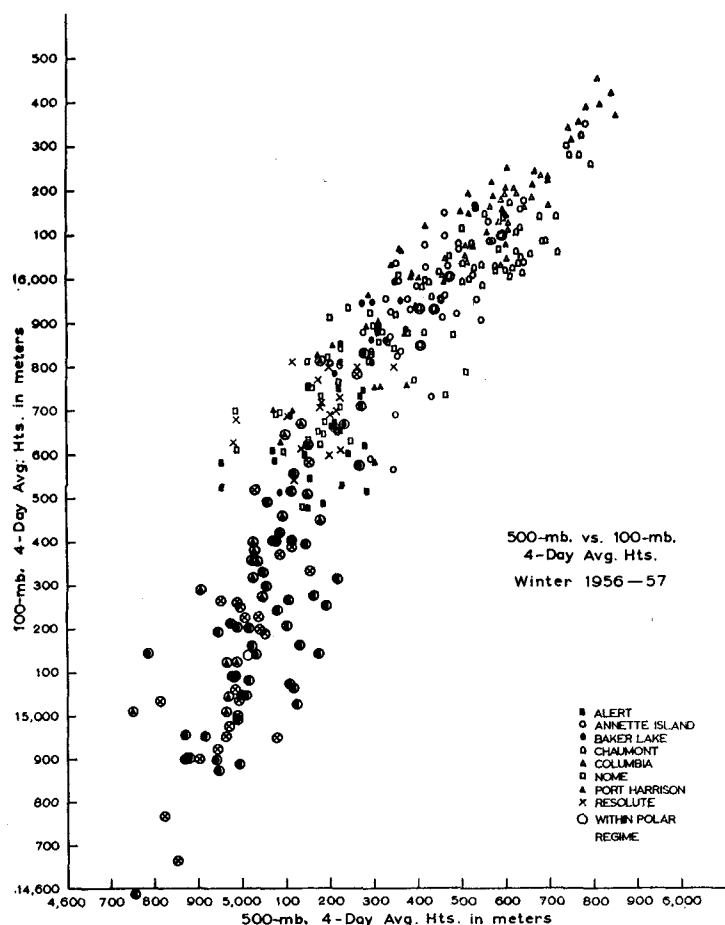
FIGURE 7.—Four-day average 100-mb. heights versus four-day average 500-mb. heights for winter 1956–57. The symbols representing periods in the polar regime are circled.

FIGURE 8.—Four-day average 100-mb. heights versus four-day average 500-mb. heights for winter 1955–56.

have a vertical axis throughout the stratosphere to at least 10 mb. Mean maps at 100 mb. show trough positions over eastern Canada, eastern Siberia, and Novaya Zemlya. On the other hand, ridges are indicated over Alaska and Western Europe (Heastie [5]).

A further important difference between the polar regime and the LSR is illustrated by figures 1 and 2. Here the spectral estimates are multiplied by frequency in order that area represent variance on a logarithmic scale of periods. These figures contrast spectra of height at 500 mb. and 100 mb. on the two sides of the PRB. As pointed out above, on both sides the relative contribution of high frequencies to the variances of height is always greater at 500 mb. The important difference between the two regimes, however, lies in the enormous amount of variance produced by low frequency fluctuations (periods above 20 days) in the polar regime at 100 mb. This variance is associated with the gradual drift of the polar vortex noted above, or with slow deepening or filling of the vortex. The strong baroclinity associated with the stratospheric
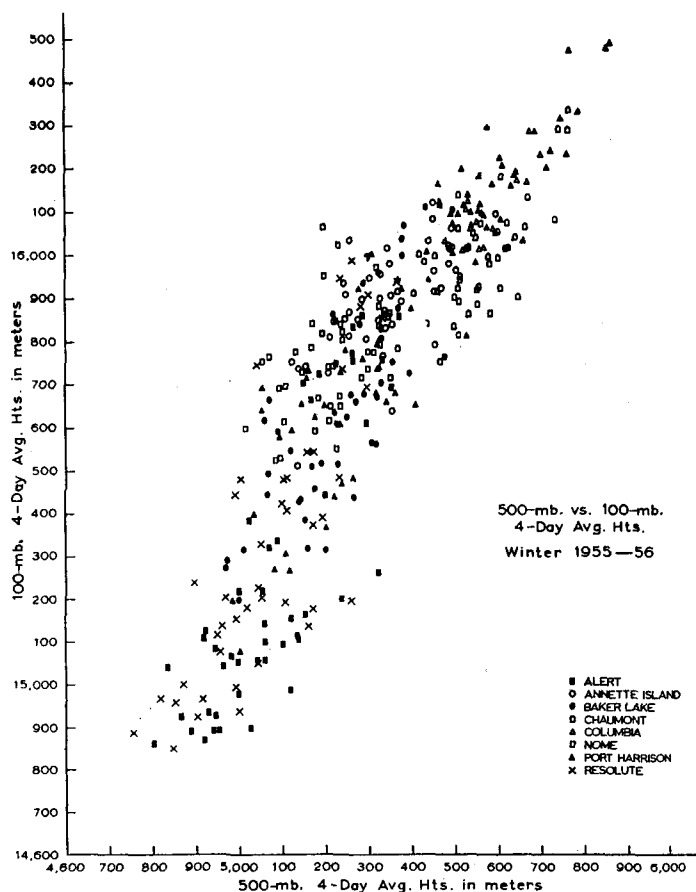
cooling in the polar night is a logical source of this energy.

Outside of the polar vortex, however, the difference between the spectra at 500 mb. and 100 mb. can be understood by assuming that the energy is created in the troposphere and damped upward above the tropopause, with the damping being most effective at high frequencies.

The polar regime usually begins to form in September as the strong radiative cooling of the polar night begins and continues to increase in intensity until the end of December. Its disappearance may be quite sudden, occurring some time between the beginning of January and the end of March in the winters thus far examined (1950 to 1958). The date of the beginning of this breakup, as well as the intensity of the breakup, is quite different in different winters. Further, each winter seems to be unique in the strength and preferred position of the vortex.

Many of these phenomena have also been described by Scherhag [10], Godson et al. [3], Godson and Lee [4], Teweles [11], Teweles and Finger [12], Craig and Hering [2], and Warnecke [13].
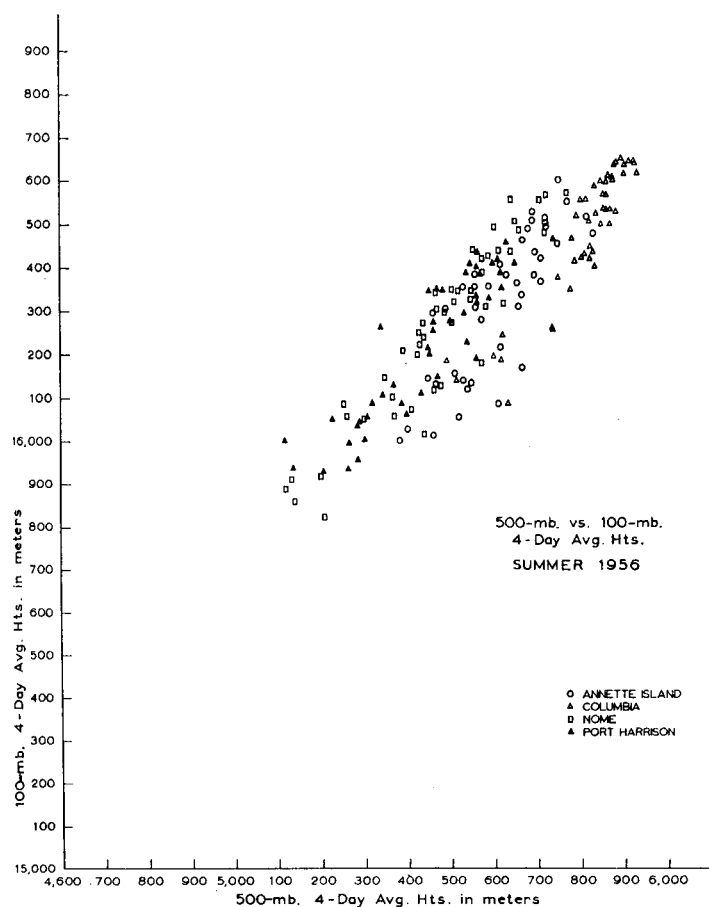
FIGURE 9.—Four-day average 100-mb. heights versus four-day average 500-mb. heights for summer 1956.
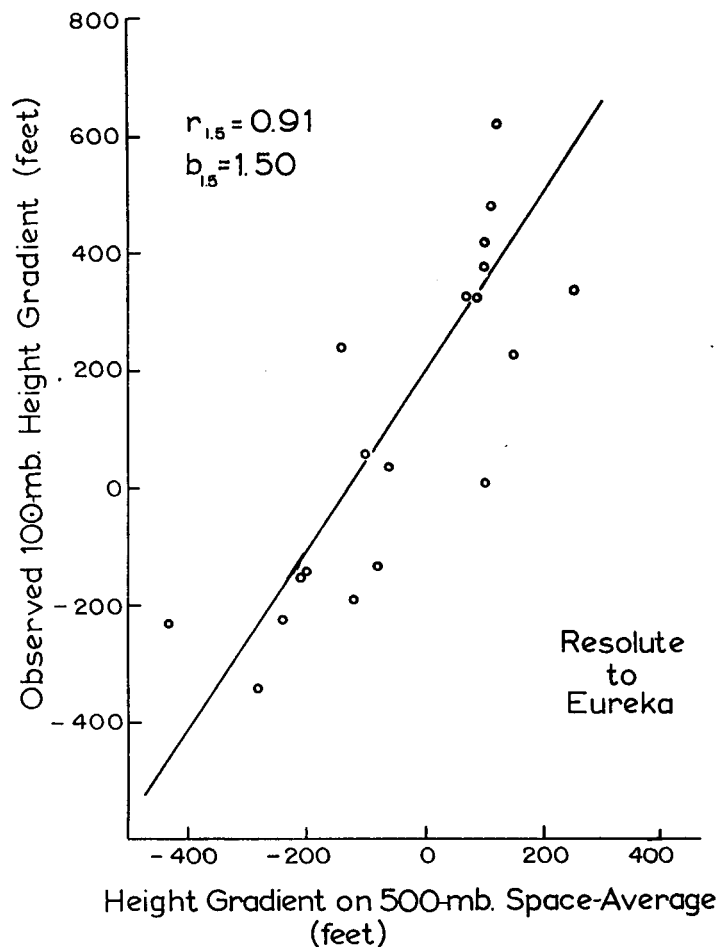

FIGURE 10.—Observed 100-mb. height gradient versus the height gradient on the space-averaged 500-mb. chart between Resolute and Eureka, Canada during winter 1956–57.

3. COMPARISON BETWEEN SPACE-MEAN 500-MB. FLOW AND 100-MB. FLOW

Figures 3 and 4 compare the 500-mb. height distribution, smoothed by the AROWA 20° diamond space mean (see Berry, Haggard, and Wolff [1]), for 0300 GMT, December 30, 1956, with the 100-mb. height distribution. In many ways this situation is typical for a winter with a well developed vortex. The 100-mb. flow shows a vortex with wave numbers two and three predominating; also the PRB is located in figure 4.

Equatorward of the PRB the 100-mb. flow shows a remarkable similarity to the space-mean 500-mb. flow with, of course, the horizontal temperature gradient reversed. Between latitude 35° and the PRB, the wind speeds are about equal at the two levels. South of 35° there is a tendency for the 100-mb. speeds to exceed those at 500 mb. at least in the areas of adequate data. In all cases, the trough-ridge positions at the two levels match as well as can be expected. This means that wind directions on the two charts are well correlated.

A study involving three independent 10-day periods in each of three winters was undertaken to test the degree of correspondence of the space-averaged 500-mb. and 100-mb. charts. Geostrophic winds were evaluated at a series of grid points covering the United States and southern Canada, and root-mean-square speed and direction differences formed. At all grid points root-mean-square direction differences averaged 19 degrees, varying over the periods involved from 11 to 25 degrees. The speed differences were strongly a function of latitude; at 30° the speeds averaged consistently 15 knots greater at 100 mb. than at 500 mb. At 40°, the differences averaged from 0 to 27 knots, and at 50°, from 4 to 29 knots. At 40° and 50° the speed differences are strongly affected by the degree of strength of the stratospheric vortex circulation. At 30° the tropopause is near 100 mb., no temperature compensation exists, and the 100-mb. speeds are correspondingly greater. At 40° the matching level is near 100 mb., if the polar vortex does not affect this latitude.

Perhaps rather unexpectedly, wind directions seem to be matched well inside the PRB. Of course, the spacing
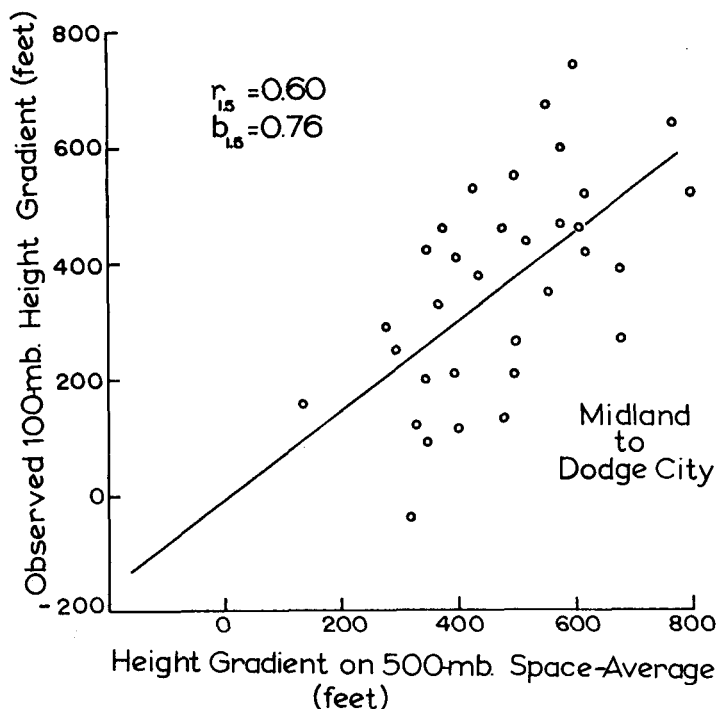
FIGURE 11.—Observed 100-mb. height gradient versus the height gradient on space-averaged 500-mb. chart between Midland, Tex. and Dodge City, Kans. during winter 1956–57.

of the contours in the polar regime is considerably closer at 100 mb. than at 500 mb. This more intense circulation in the stratospheric polar circulation in winter will be analyzed in greater detail later.

Figures 5 and 6 compare a 500-mb. space-mean chart in summer, June 30, 1957, with the corresponding 100-mb. chart. The tropospheric systems (in middle and high latitudes) are quite recognizable at 100 mb., although the speeds at the higher level are generally weaker than the space-mean gradients. Examination of vertical wind speed profiles indicates the "level of match" to be about 125 mb. at latitude 40° N. lowering to 150 mb. at latitude 60° N. Again, emphasis must be placed on recognition that the matching level idea is restricted to regions in which temperature compensation occurs between the upper troposphere and lower stratosphere. Thus the subtropical Highs and regions wherein the tropical tropopause is present cannot be expected to show such characteristics. This can easily be seen by examining wind profiles in the southern United States for the June 30, 1957 maps shown.

4. DIFFERENCES
IN THE STRATOSPHERE-TROPOSPHERE RELATIONS
ON THE TWO SIDES OF THE PRB

For eleven stations (1 in Missouri, 1 in France, 7 in Canada, and 2 in Alaska), 4-day average heights at 500 mb. were compared with simultaneous 4-day average
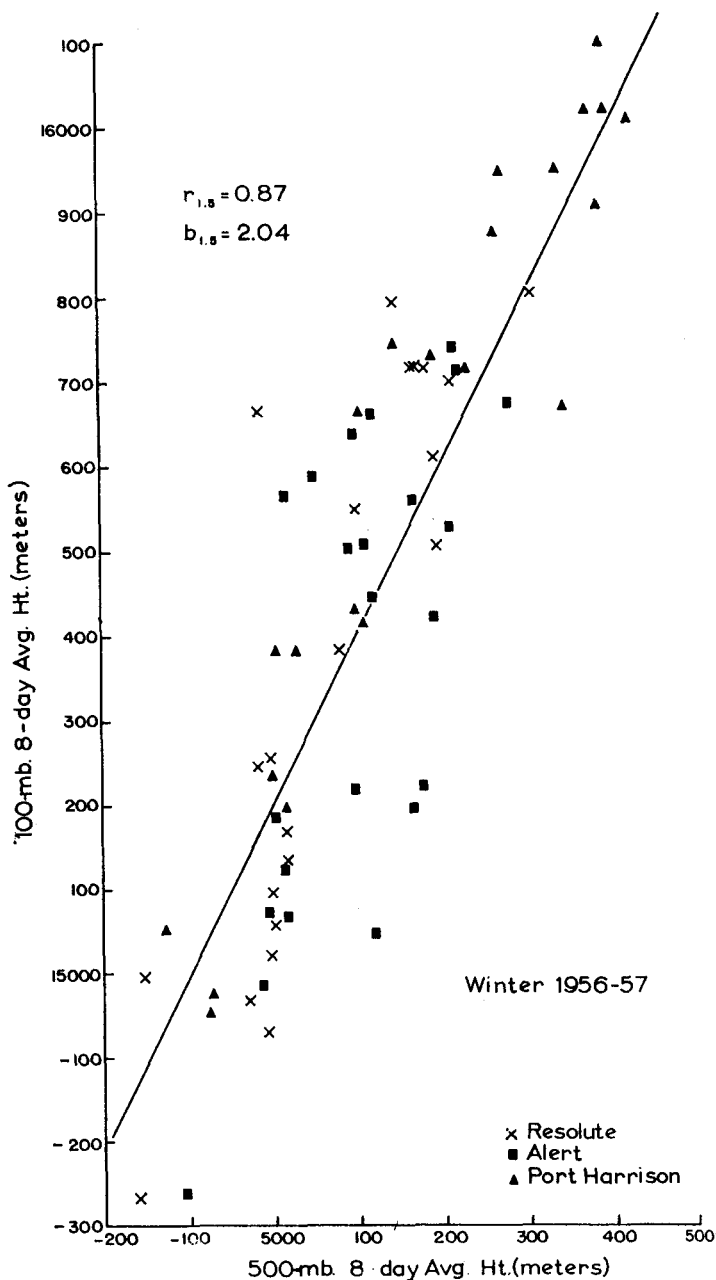

FIGURE 12.—Eight-day average 100-mb. heights versus eight-day average 500-mb. heights within the polar regime during winter 1956–57.

heights at 100 mb. These quantities will be simply referred to as "heights." The observations covered four winters (defined as the period from October through March), from the 1953–54 season to the 1956–57 season. The remaining periods of the years 1955, 1956, and 1957 were defined as "summer" and analysed separately.

Figure 7 shows the relationship betwen 500-mb. and 100-mb. height for stations which were on different sides of the polar regime boundary (PRB) at different times. Points representing observations at times when the station was inside the PRB are circled. A station was de-
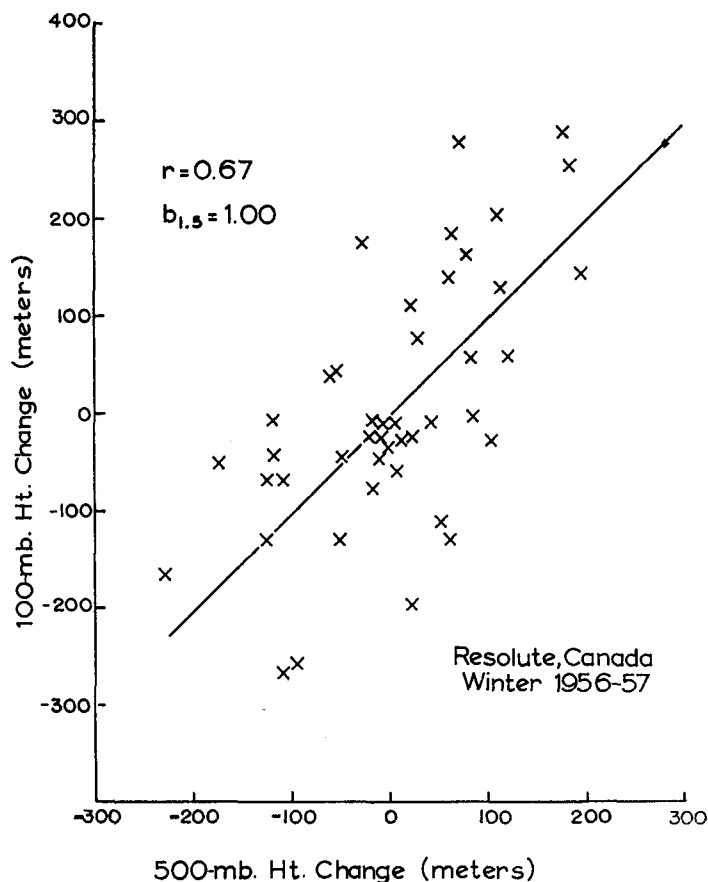
FIGURE 13.—Change in four-day average 100-mb. height versus the change in 4-day average 500-mb. height at Resolute, Canada during winter 1956–57.

FIGURE 14.—Change in four-day average 100-mb. height versus the change in four-day average 500-mb. height at Chaumont, France during winter 1956–57.

fined to be within the PRB when its height tendency and temperature tendency had the same sign. The figure suggests generally that there is a good relation between the heights at the two levels.

Figure 7 serves to illustrate a basic difference between the stratosphere-troposphere height relationships on the two sides of the PRB: outside the PRB, the slope of a line of regression for 100-mb. height as function of 500-mb. height does not differ much from unity, indicating stratosphere-troposphere temperature compensation; inside the PRB, in the polar regime, the slope is considerably greater than unity, showing that compensation is absent or incomplete. Figure 8 illustrates the same features for another winter season. Figure 9, on the other hand, was obtained from summer observations. In summer, no polar regime exists and all observations are consistent with the hypothesis that the relation between heights at the two levels has a slope of about unity in the LSR.

That a similar difference in the winds exists in the PR and LSR was already made plausible in the last section; this point is further illustrated by figures 10 and 11. These figures contrast the relation between geostrophic
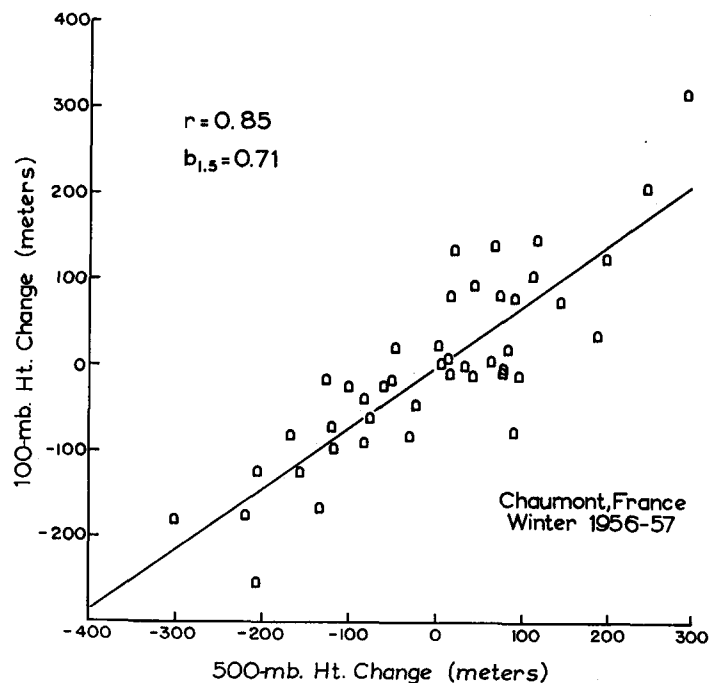
wind components at 100 mb. and 500 mb. in a region dominated by the polar regime and in a low-latitude region. Again, the wind fluctuations in the polar regime are greater at 100 mb. than at 500 mb., but of the same general magnitude outside of the PRB.

It was shown in section 2 that the spectra of the heights inside the polar regime in the stratosphere are characterized by an enormous amount of low-frequency variance corresponding to periods greater than 20 days. The question may be raised whether the large ratio of 100-mb. variations to 500-mb. variations is associated with these large and gradual variations. If that were true, one would expect that the slow fluctuations of height at 100 mb. would be of a much greater magnitude than those at 500 mb., whereas the high-frequency behavior at the two levels would be similar. That this is indeed the case is demonstrated by figures 12 and 13.

Figure 12 shows the relation between 8-day mean heights at 500 mb. and 100 mb. The effect of taking 8-day means is to filter out practically all energy of height fluctuations with periods less than 8 days, and more than one-half the energy of oscillations of the order of 16 days. In other words, the bulk of the variation indicated by figure 12 is due to fluctuations with periods exceeding 16 days. Apparently, the correlation between 500 mb. and 100 mb. is quite large, but the magnitudes of the changes at 100 mb. are more than twice those at 500 mb.

Figure 13 shows the relation between height changes at 500 and 100 mb., rather than heights, inside the polar
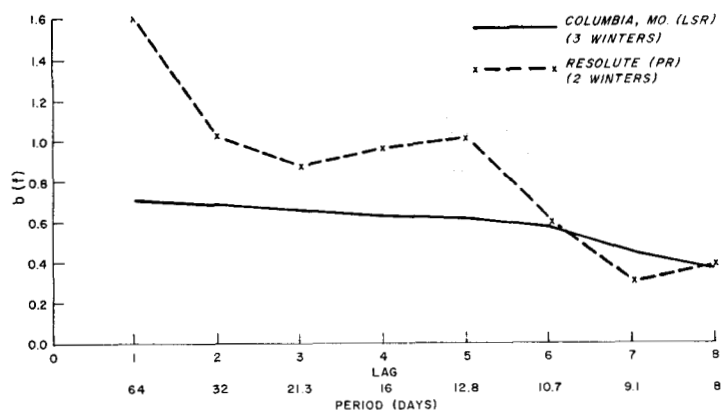
FIGURE 15.—Ratio of cospectrum (500–100 mb.) to spectrum (500 mb.) for lower-stratosphere regime (LSR) and polar regime (PR) stations.

vortex. As before, the term "height" here refers to 4-day averages. It can be shown (Holloway [6]) that height changes (as compared to heights) are mostly influenced by the high-frequency components of the height spectra. Of course, these changes are also influenced relatively strongly by errors of observation, a fact which explains at least part of the large scatter evident in figure 13. Nevertheless, the figure makes plausible the conclusion that, in the polar vortex region, height fluctuations with periods of 8 days or less at 100 mb. and 500 mb. are of the same general magnitude.

Outside the polar regime, even the slow height fluctuations are of the same order of magnitude at 500 mb. and 100 mb. This fact is demonstrated by figure 14. It is reasonable to assume that these variations are greatest at about the level of the tropopause, and thus of about the same magnitude at 500 mb. and 100 mb. The compensation between stratospheric and tropospheric temperature changes here is good.

The fact that the relationship between 500 mb. and 100 mb. in the PR depends on scale was further confirmed by the cross-spectrum analysis between the heights at the two levels. We can define a quantity $b(f)$ by:

$$b(f) = \frac{C(f)}{S(f)};$$

here $C(f)$ is the cospectrum between 500-mb. and 100-mb. heights, and $S(f)$ is the spectrum of 500-mb. heights. The quantity $b(f)$ can be interpreted as the regression coefficient at frequency f, which would be needed to estimate a given harmonic at 100 mb. from the same harmonic at 500 mb. As figure 15 shows, $b(f)$ decreases with increasing frequency, as would be expected from the arguments given above.

5. THE VARIATIONS OF WINDS AT 500 MB. AND 100 MB.

The influence of the position of the PRB on the relation between 500-mb. and 100-mb. flow is further illus-
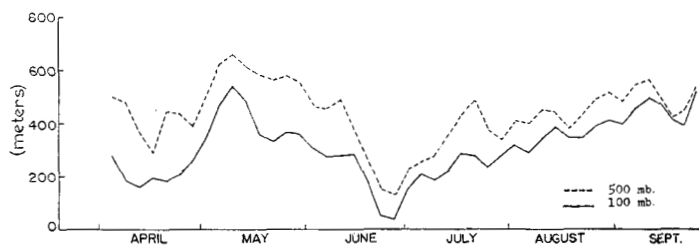

FIGURE 16.—Contour height difference, Columbia, Mo. to Resolute, Canada during summer 1956. These are 8-day running averages (4-day overlap).
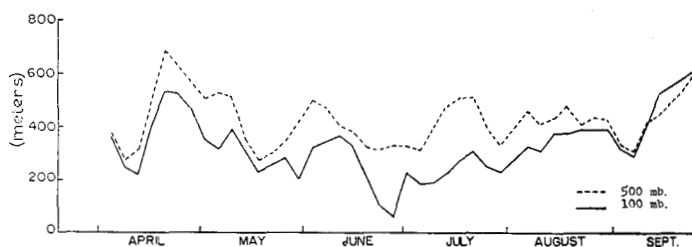

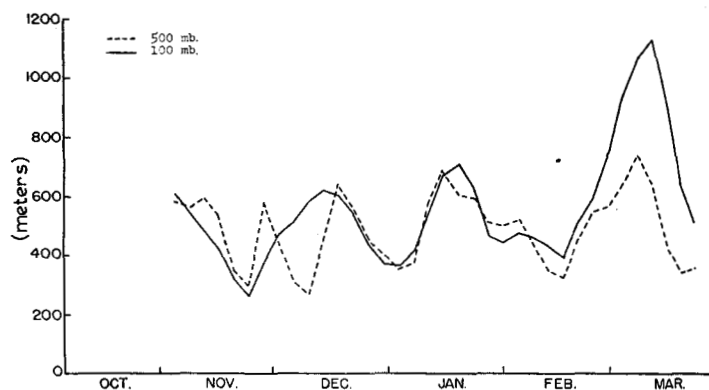FIGURE 17.—Contour height difference, Columbia, Mo. to Resolute, Canada during summer 1957.

FIGURE 18.—Contour height difference, Columbia, Mo. to Resolute, Canada during winter 1952–53.

trated by figures 16–20. Here the 8-day mean height gradient between Columbia, Mo., and Resolute Bay is traced through two summers and three winters. This quantity of course, gives an average geostrophic wind component at right angles to the line connecting the two stations.

There is not much difference between the two summer seasons; the variations in height difference at 500 mb. and 100 mb. are extremely well correlated with each other. Numerically, the height gradient at 100 mb. averages about
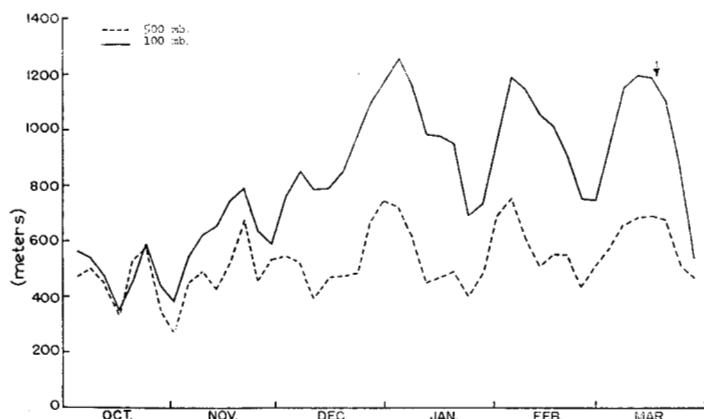
FIGURE 19.—Contour height difference, Columbia, Mo. to Resolute, Canada during winter 1955–56.
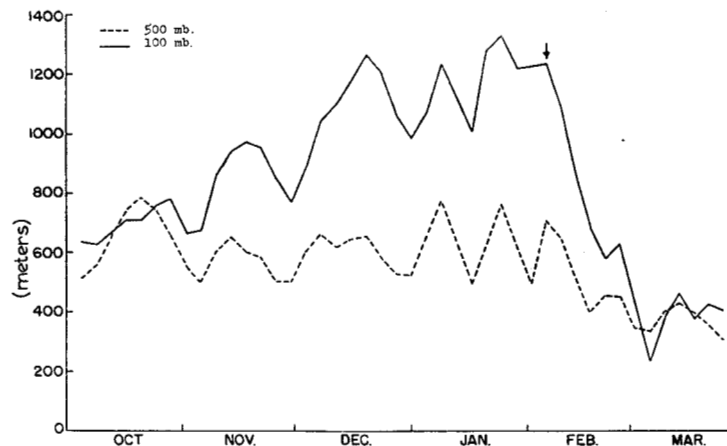

FIGURE 20.—Contour height difference, Columbia, Mo. to Resolute, Canada during winter 1956–57.

100 m. less than that at 500 mb. This result is not inconsistent with the observations discussed in section 3.

The behavior of the geostrophic winds in the three winter seasons is more varied: in all seasons, again, the changes of wind with time at the two levels are well correlated; however, the difference in wind speed at the two levels is by no means constant. For example, in winter 1955–56, the difference steadily increased from the beginning of November to the end of December (with the 100-mb. flow being the faster), then remained about constant until the second half of March when it dropped rather suddenly to zero. In 1956–57 a similar build-up of difference in wind occurred, with a sudden drop at the beginning of February. Only in the winter 1952–53 did the difference remain small, except for a short period at the beginning of March.

The differences among the winds in the various seasons are clearly related to the differing behavior of the polar vortex. For, as pointed out previously, the polar vortex results in relatively faster winds at 100 mb. than at 500 mb. Thus, for example, the polar vortex often makes its appearance in the North American section at the beginning of November, builds up to maximum intensity at the end of December, and then weakens rather suddenly at some time between January and March. In 1957, the polar vortex weakened rapidly during the time of the frequently-studied period of "explosive" warming at the end of January and beginning of February; in 1956, however, the vortex remained strong through March. For January, February, and March, 1953, we fortunately have the U.S. Weather Bureau series of daily 100-mb. and 50-mb. charts, constructed by Moreland and Cluff [9]. These maps, although dependent almost wholly on extrapolated data in the polar regions, show that in this season the vortex center was relatively far from the pole, on the Eurasian side, so that there was no large effect in the North American sector. Only in the beginning of March, when the

vortex slowly drifted across the pole, did its influence become apparent over North America for a week or two before the usual weakening of early spring.

Of course, even when the influence of the polar vortex is strongest, the 100-mb. average wind speed between Columbia and Resolute Bay is not quite twice the wind speed at 500 mb., as might have been expected from the previous discussion. The reason is that only a variable amount of the northern portion of the line from Resolute Bay to Columbia is affected by the circulation around the vortex.

To summarize these results, the relation between 500-mb. and 100-mb. flow in winter north of 35° N. is dominated by the position and intensity of the vortex. When the vortex is absent, 500-mb. space-mean winds are equal to or even faster than 100-mb. winds; on the other hand, if influenced by the vortex, the 100-mb. winds are, by far, faster than 500-mb. winds.

6. SUMMARY

Examination of numerous simultaneous 100-mb. and 500-mb. charts has indicated that the basic long-wave structure of the upper troposphere is preserved in the lower stratosphere to at least 100 mb. In middle latitudes cooling below the tropopause level tends to be compensated by warming in the lower stratosphere, and vice versa. Removal of the shorter wavelength disturbances associated with strongly baroclinic systems at 500 mb. by a suitable space-mean process produces a reasonable mid- and high-latitude 100-mb. flow pattern in all seasons of the year, with some exceptions.

The major exception occurs in winter when strong radiative cooling of the stratosphere produces a cold vortex circulation which reverses the usual poleward temperature gradient in polar latitudes and prevents troposphere-stratosphere compensation. Strong westerlies are thus to be expected at 100 mb., being roughly twice the speed of the 500-mb. space-mean winds in comparable latitudes.

Each winter exhibits uniqueness with respect to the vortex intensity and vortex location. In spite of the uncertainty thus produced in the strength of the 100-mb. flow, the long-wave ridge-trough positions, as well as the vortex center, are generally well specified by means of the 500-mb. space-mean chart. Spectra of height changes within the polar vortex indicate that the larger changes at 100 mb. are associated with large-scale height fluctuations (periods greater than about 20 days).

Equatorward of the polar vortex, in the LSR, (outside of the Tropics) the height changes at 500 mb. and 100 mb. are of the same order of magnitude, and the intensity of the circulation, which has its maximum at tropopause level, diminishes upward.

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